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Original article

Mona Lisa's *spolvero* revealed

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ABSTRACT

On the request of the Louvre Museum, *Mona Lisa*'s portrait was digitised with Lumiere Technology's high-resolution multispectral camera.

The data from this digitisation revealed for the first time the *spolvero* (a drawing transfer technique) of the portrait. These discoveries change the history of this iconic symbol of Western painting because they are proof that a preparatory drawing was employed.

These discoveries were possible because the multispectral camera produces high-resolution images of 13 filters, including 3 IR filters with a high signal-to-noise ratio and optimal spatial resolution. The images are processed with the layer amplification method (L.A.M.), which amplifies weak signals and thus reveals new details. A test board was made to compare the L.A.M. with traditional IR reflectography.

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1. Introduction

The Mona Lisa, the icon of Western painting, painted at the very beginning of the 16th century by Leonardo da Vinci needs no introduction. The painting was born in a time when the tradition was to paint on wood, in this case, poplar. The wood to be painted undergoes a long preparation process involving 7–10 years of drying and the slow application of several layers of gesso and glue or lead white, which make the surface to be painted bright, smooth, and silky to the touch. Only then can the artist can begin a project. Leonardo da Vinci di Ser Pietro apprenticed in Master Verrocchio's workshop. The method of preparing a pictorial composition that he learned comprised making a drawing on paper then transferring it onto the plank by the method of *spolvero*, whereby the drawing is perforated with a needle, producing holes along the contours. The paper is then placed on the plank, and a powder of black pigment is applied, leaving a series of black dots. This method is described by Cennini in the 15th century [1]. There are many *spolveri* in other portraits painted by Leonardo, for instance, *The Lady with an Ermine* [2], *Ginevra de'Benci* [3,4] and *La Belle Ferronnière* [5]. Therefore, it was surprising that none were discovered in *Mona Lisa*.

The traditional means of observing *spolvero* under paintings is to use IR photography and IR reflectography. In the 1950s, photographic films (850 nm) were used, and in 1990s, analogue cameras based on the Vidicon tube were used (1100–2000 nm). The arrival

of CCD (380–1050 nm), followed by the InGaAs sensor (gallium arsenide and indium) band 900–1700 nm, and the InSb sensor (indium antimonide) band 1000–2450 nm, have improved the performance of IR cameras, making it possible to see ever deeper with infrared. Most authors have claimed that the farther the infrared rays, the more underlying drawings become apparent [6–8].

In the last study of the *Mona Lisa*, which benefited from the most state-of-the-art technical means available in 2004–2006, the Louvre's IR investigations highlighted some restorations—one repaint on the fingers of the left hand, construction details of the armrest, and an interlacing under the veil of the left shoulder—but no mention of the presence of *spolvero* was reported in their publication [9]. In 2019, despite modern means, there is no evidence to affirm the presence of this technique in this work [10].

2. Research aim

This article outlines and explains our methodology employed to highlight the *Mona Lisa*'s *spolvero*. We first present the performance in terms of signal-to-noise ratio (SNR) and the spatial resolution of the camera, as well as the multispectral imaging treatments we applied, including the layer amplification method (L.A.M.). To validate the approach, a test board is conducted and the method is compared with IR reflectography. Finally, the highlighting of the *spolvero* on the *Mona Lisa* is presented.

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Fig. 1. Mona Lisa's multispectral scanning.

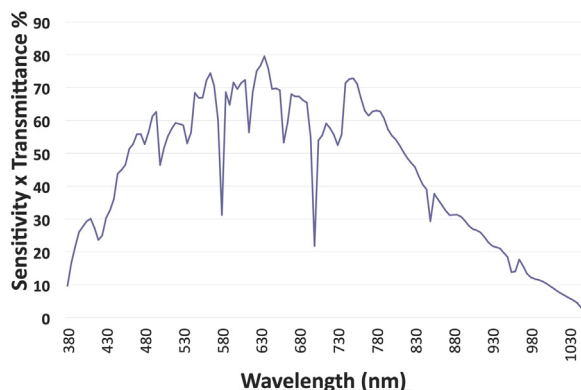


Fig. 2. Quantum Efficiency $\times$ Filters transmittance of the camera.

3. The multispectral camera

Inside the Louvre Museum, a multispectral camera [11] digitised the *Mona Lisa* [12–14] (Fig. 1).

3.1. Performances of the camera

Lumiere Technology developed of this camera in the framework of the project CRISATEL, European Research Programme IST2. The fundamental technical characteristics have been designed to offer maximal optical and electronic performance. A CCD sensor is used with 13 filters that divide the visible and near-infrared (NIR) light spectrum. The whole has good efficiency in the spectral range [380–1050 nm] (Fig. 2).

The multispectral camera uses a TH-7834 CCD sensor originally designed for the SPOT [15] image weather satellite. It is a 12,000 pixel linear array of a 6.5 μm square. It offers a dynamic range (DR)

of 10,000:1 [16] and an effective SNR of 9, 230:1, or 79.3 dB (see Appendix A).

The camera uses a 210 mm focal length optic and a symmetrical lens formula. Geometric distortion is low and not measurable.

One of the main optical characteristics of this camera is its ability to memorise a specific focus for each filter with 2 advantages: always having a maximum contrast transfer function (CTF) for each wavelength (in appendix B are the measurements of the ISO 16097-1 test pattern [17]) and the cancelling of sagittal and longitudinal chromatic aberration, defects that are inevitable otherwise. This is a second considerable technical advantage compared with hyperspectral cameras because the focus and therefore the resolution are optimised for one wavelength and are significantly worse at the edge of the spectrum.

We increase the DR of the image by using the binning method [18]. We use a binning of max 4×4 pixels, and therefore there is a gain in SNR of 10 dB (Appendix C).

3.2. Multispectral image processing

The processing techniques specific to multi- and hyperspectral imaging are derived from methods developed for satellite imagery, among which are spectral angle mapping [19] and spectral correlation mapping [20]. There are classification methods for assessing the similarity of spectra to a reference used, for example, to identify spectra of areas, for example, forest or agricultural, or in the case of works of art to identify pigments.

For the detection of underlying drawings, the problem is different because the carbon black pigment used for *spolvero* has no spectral signature. The aim is to detect very small spectral differences related to carbon black, obviously without a priori knowledge of the area where the underlying drawings are located. The usual contrast-enhancement techniques for each spectral band, especially in IR, are a first approach, but in most cases, they are insufficient.

The pictorial layers of old, classic paintings are generally approximately 1 mm thick, and their optical properties (absorption and scattering) allow the light to penetrate them according to the wavelength. However, the extreme complexity of the interaction of light and matter involves all the components of the pictorial layer: the surface varnish, the varieties of pigments, the sizes of the pigment grains and their shape, the binders (e.g. oil, mastic, wax, egg), the driers (e.g. lead), additives (e.g. glues, varnishes, mastics, glass), their preparation method, superposed pigment layers, the thickness of each layer, preparatory drawings and surface preparations (e.g. calcium carbonate, calcite), and ageing factors of materials. Without precise knowledge of the structure of the pictorial layer, it is impossible to establish a prediction model to obtain an image in the exact depth desired. To overcome this apparent impossibility, some methods combine images from 2 or more filters [21,22]. The L.A.M. technique is a protocol that generalises this approach, and various calculations are performed with variable coefficients to increase the contrast. Stretching and equalising the histogram based on Shannon entropy extends the dynamics of the resulting images [23].

All these calculations produce many images. Similar to medical echography, a single echo image is difficult to understand without observing the other images. Therefore, to make the technique efficient, the images are watched at a video rate of several per second, and the remarkable ones are isolated. All the L.A.M. images are recalculated for each interesting detail and the contrast optimised. The images of the detail are displayed as thumbnails on large photo plates for a quicker selection. For the same detail, it is often interesting to superimpose the information given by several L.A.M. images to complete it and form an opinion when there is a doubt about an observation. As with any detection technique, our method can

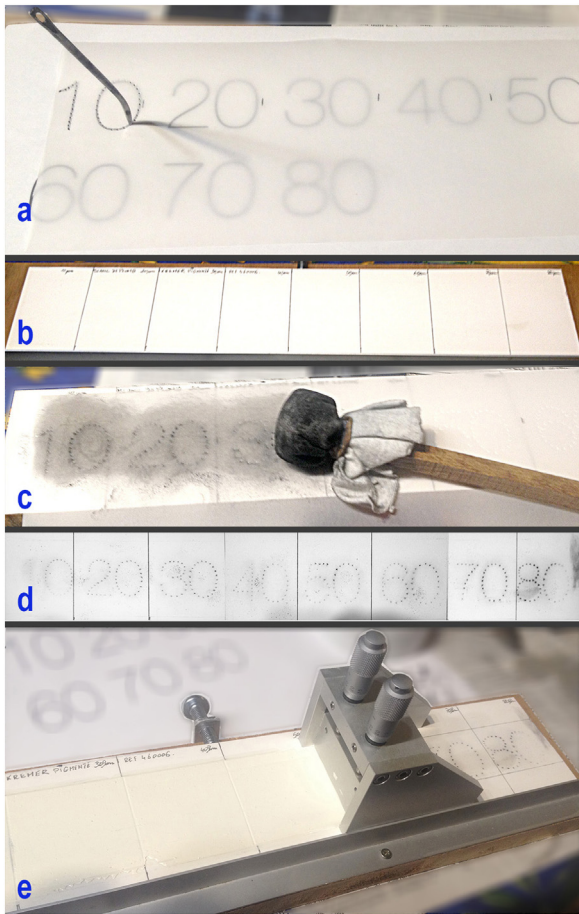


Fig. 3. Making a test board with an increasing thickness of lead white covering spolveri.

present false positives. Thus, this type of analysis must be entrusted to a technical expert who verifies that the information is found in several wavelength combinations. The expert must have the knowledge required to select the best L.A.M. image and be a specialist in painting techniques to correctly interpret the detected signals.

This method has been spread by and taught at Bologna University, *Alma Mater Studiorum*. It is widely used for analysing paintings [2], drawings, and palimpsests [24]. This method completes the list of scientific examinations conducted on works of art to analyse the lower layers of the pictorial matter to find, for example, preparatory drawings, repaints, and restoration. In most cases, this method provides better results than IR reflectography.

4. Validation of the method and comparison with IR reflectography

To illustrate the difficulty of detecting *spolvero*, namely, by IR reflectance, and test the effectiveness of the proposed method, we perform a test board (Fig. 3) with known materials, thicknesses, and pattern. This test is founded on the method of *spolvero* used by Leonardo da Vinci to prepare a painting.

- A transparent sheet is pierced with needle holes following the contours to make a *spolvero*;
- A wooden board covered with white gesso is divided into 8 zones;
- A very fine carbon black powder is applied on the transparent sheet to make the *spolvero* on the gesso;
- This process leaves the *spolvero*, a series of black dots on the gesso;

- Using a micrometric paint applicator (10 μm step), increasing thicknesses of lead white are applied on each area. The paint is made with lead white mixed with 17% vol. of walnuts oil with litharge. The fluidity is 450 poises.

The thickness was measured after 1 year. The fluidity of the paint and the oxidation of the binder over time considerably reduce the final thickness. Due to the irregularities in the surfaces of the wooden support, there are important variations in the thicknesses of the lead white layer when dry, and they are presented as an indication in Table 1.

To the naked eye (Fig. 4 observing the final product, the *spolvero* is a little visible in zones 10 and 20 (10 and 20 μm thick), nearly disappears in zone 30 (70 μm), and is invisible in the remaining zones with thicker layers.

4.1. Comparison of imaging results

4.1.1. OSIRIS camera – IR Reflectography 1700 nm

A new camera in 2016 featuring an internal mechanical scanning system able to create high-quality images of 16 M. pixels was used to perform infrared reflectography at 1700 nm on this test board; the same was used by the Louvre for the *Mona Lisa* [30]. Two halogen lamps illuminate the test board. This type of IR *InGaAs* image sensor has traditionally been used in many museum laboratories [25]. To ensure that the results are comparable with L.A.M. images, the histogram of the image (Fig. 4b) has been stretched and equalised. The image shows the *spolvero* 30 (70 μm thick of lead white) but struggles with the *spolvero* 40, where the contour is barely perceptible. The other *spolveri* remain invisible.

4.1.2. Use of the multispectral camera with a 1000 nm IR filter

The image obtained by the 1000 nm filter of the multispectral camera is presented in Fig. 4c, whose histogram has been stretched and equalised as it was on the 1700 nm IR reflectography (Fig. 4b). The 2 images obtained are comparable: The *spolvero* 40 remains difficult to observe. For this example, scanning at 1700 nm offers no advantage over scanning at 1000 nm.

4.1.3. L.A.M. technique with the multispectral camera

The L.A.M. technique (Fig. 4d) shows the *spolveri* of the 30 (70 μm), 40 (180 μm), and 50 (270 μm) and the contours of the 60 (350 μm) and 70 (360 μm).

Zones 10, 20, and 30 are the result of an L.A.M. from the same calculation, and zones 40, 50, 60, and 70 are from 4 different calculations.

4.2. Results analysis

This difference in results obtained by using the L.A.M. technique and NIR reflectography is partially explained by the 2 main technical characteristics of the camera previously exposed in part 1: its good CTF and SNR, with the use of multiple NIR narrow filters and the camera's high resolution of 240,000,000 pixels. The image quality allows high amplification (approximately 1:4000) of weak signals and high discrimination of information.

However, other characteristics accentuate this difference: The CTF for IR wavelengths greater than 1000 nm is lower than the CTF in the visible range because as the wavelength increases, the diffraction limit induces a decrease of the spatial resolution. The minimum size with a numerical optical aperture of $N=8$ (used by the multispectral camera), according to the Rayleigh criterion ($1.22\lambda/N$), is 5.4 μm for 550 nm (median value visible spectrum), and it is 16.6 μm for 1700 nm and 24.4 μm for 2500 nm. The resolution at 1700 nm, resp. 2500 nm, is therefore ~ 10 times, resp. ~ 25 times lower than in the visible range. Of course, the wavelengths

Table 1

Thicknesses applied with the applicator (wet coat) and estimated with a micrometre comparator (when the coats are dry).

Zone	10	20	30	40	50	60	70	80
Wet	100 μm	200 μm	300 μm	400 μm	500 μm	600 μm	700 μm	800 μm
Dry	10 μm	20 μm	70 μm	180 μm	270 μm	350 μm	360 μm	370 μm

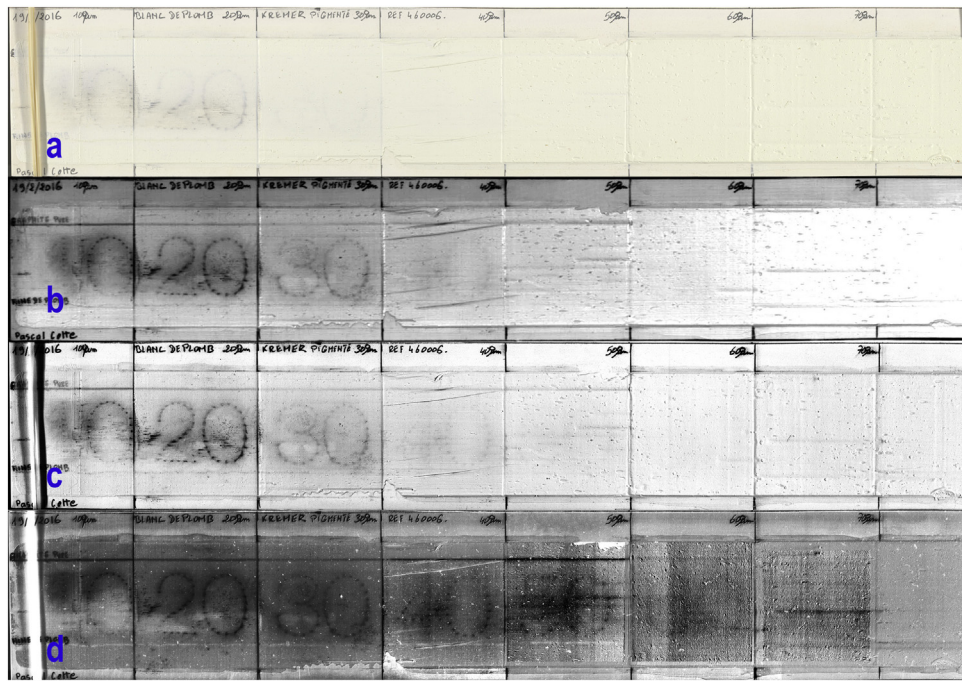


Fig. 4. Final result of the test board covered with lead white. 4a: Visible colour photography ; 4b: Osiris camera, IR Reflectography at 1700 nm. 2540 pixels $\times$ 450 pixels. ; 4c: IR image 1000 nm of the multispectral camera. 3229 pixels $\times$ 566 pixels. (after binning) ; 4d: L.A.M. Technique. 3229 pixels $\times$ 566 pixels (after binning).

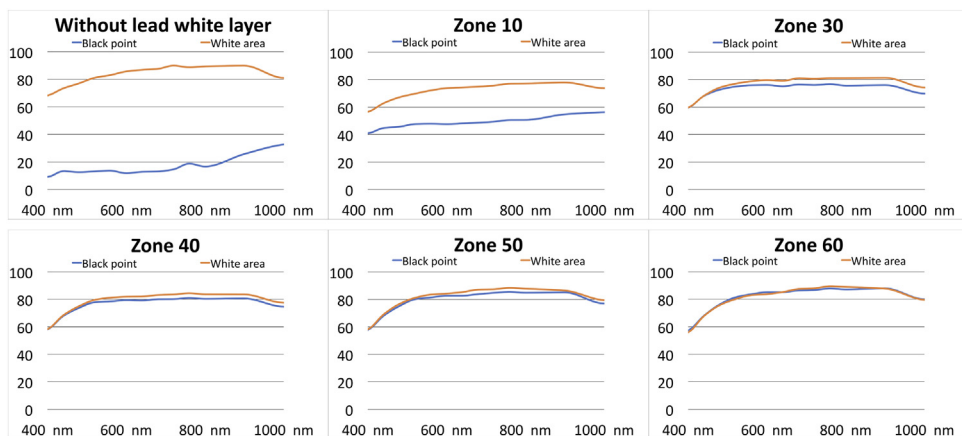


Fig. 5. Spectra of a black point (blue line) and the white area (orange line) next to it. Measurements performed on an area not covered with lead white, and on the zones 10, 30, 40, 50, 60. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

at 1700 nm or 2500 nm go more deeply inside the pictorial layer [21,22]. However, the stronger scattering of these IR wavelengths by the pictorial layer can make it impossible to detect important details, namely, the IR can go through without seeing them, located just below the surface of the painting.

On the test board scanned with the multispectral camera at 1000 dpi (39 pixels/mm), we make spectral measurements (Fig. 5) of an area corresponding to a black dot on the *spolvero*, (approx. $\varnothing$ 0.3 to 0.6 mm) and a white area immediately next to it. After calibration, we reconstruct the diffuse reflectance spectra with an average of a 9 pixel matrix (3 $\times$ 3). We calculate the CIE Lab col-

orimetric coordinates (illuminant D65) of the corresponding areas. The colour difference between the black point and the white zone is of course important ($\Delta E_{00} = 51$) when not covered with lead white. Zones 10–60, covered with lead white, respectively give $\Delta E_{00} = 13.64$ –11.11–2.09–1.52–0.82–0.65. For values below 1, we consider that visual discrimination between the 2 areas is no longer possible, which is confirmed by observation (Fig. 4a).

By analysing the reflectance spectra over the 400–1000 nm range, we observe significant differences in area 10 but irregularities in the wavelength. The greater the thickness of lead white, the smaller the difference between the curves and less the black points



Fig. 6. Locations of the 3 areas studied.

are visible. In zones 40, 50, and 60, the curves at the beginning of the visible range (400–500 nm) are almost superimposed, the difference is approximately 5% in the remaining curves for zone 40, 3%

in zone 50, and 1% in zone 60. Additionally, the greater the thickness of lead white, the more the curves converge in the infrared, to finally overlap perfectly in zone 60, and there is no difference after 900 nm: the *spolvero* cannot be detected by using only infrared. We can be assumed that the curves continue to meet after 1000 nm and beyond. This could explain why IR reflectography at 1700 nm is blind to *spolvero* if the SNR and CTF are too low and that it is better to use the visible spectrum.

For zones 30–70, filters in the central band from 500 nm to 800 nm are those that record the highest contrast, but a simple difference calculation between those filters has very little chance of providing an interesting result because the choice of filters based on this measurement is not representative of the entire image. It is necessary to find solutions that offer a more specific calculation for each pixel of the entire image and are applicable to the whole zone.

5. Results: *Mona Lisa's spolvero* revealed

To search for preparatory drawings and repaints under *Mona Lisa's* pictorial layers, the scientific team in the Louvre laboratory used 4 infrared techniques:

- 1 NIR photography (full portrait) high resolution (CCD sensor 900–1000 nm) [26]
- 2 IR reflectography (full portrait) with a camera Hamamatsu C 2400-03 IR and Vidicon tube N 2606-06 sensitive up to 2000 nm with D.R. 46 dB.

Several hundreds of shots (600×600 pixels) spaced a few centimetres apart were assembled to obtain a very high-resolution image. [27]

The face of *Mona Lisa* alone is printed in high-resolution full page and enlarged in a 300×450 mm format. [28]

- 3 NIR photography (full portrait) with the multispectral camera (800, 900, 1000 nm) [29]

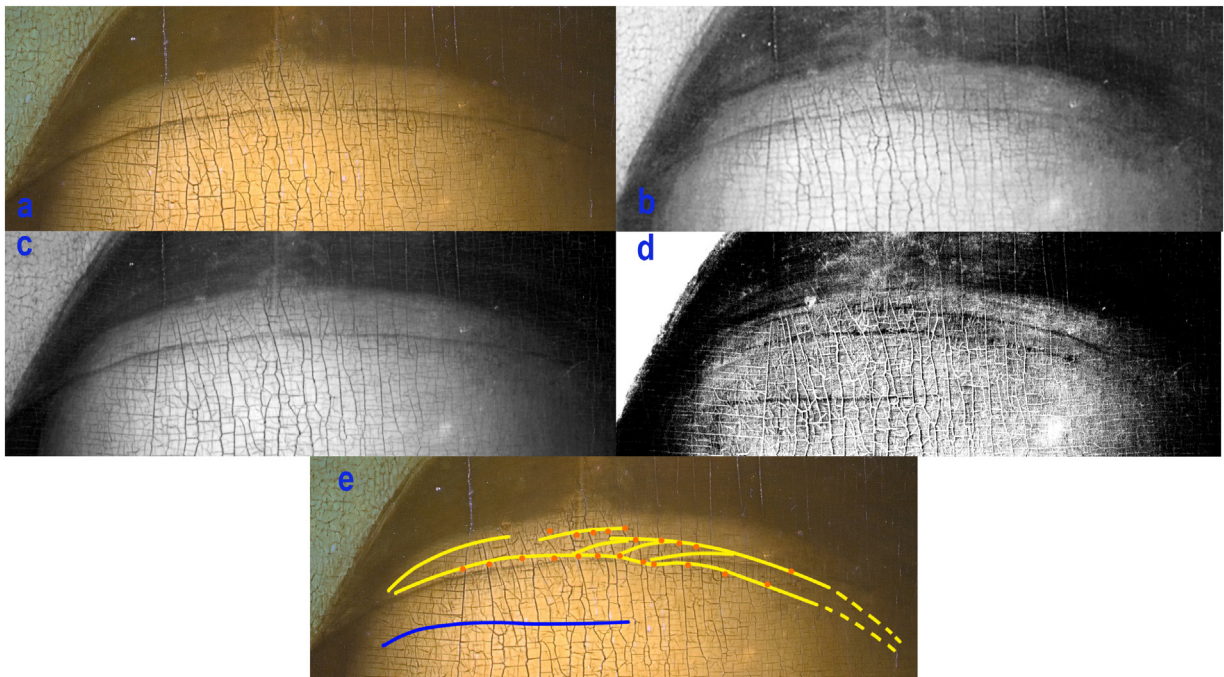


Fig. 7. Detail *Mona Lisa's* forehead: 7a – Colour image D65 ; 7b – IR reflectography 2000 nm. ©Louvre [28]; 7c- NIR filter R_{900} of the multispectral camera. ©P.Cotte; 7d – L.A.M. Technique. ©P.Cotte ; 7e – Colour image D65 + outline *spolvero*. (For interpretation of the references to colour in the text, the reader is referred to the web version of this article).

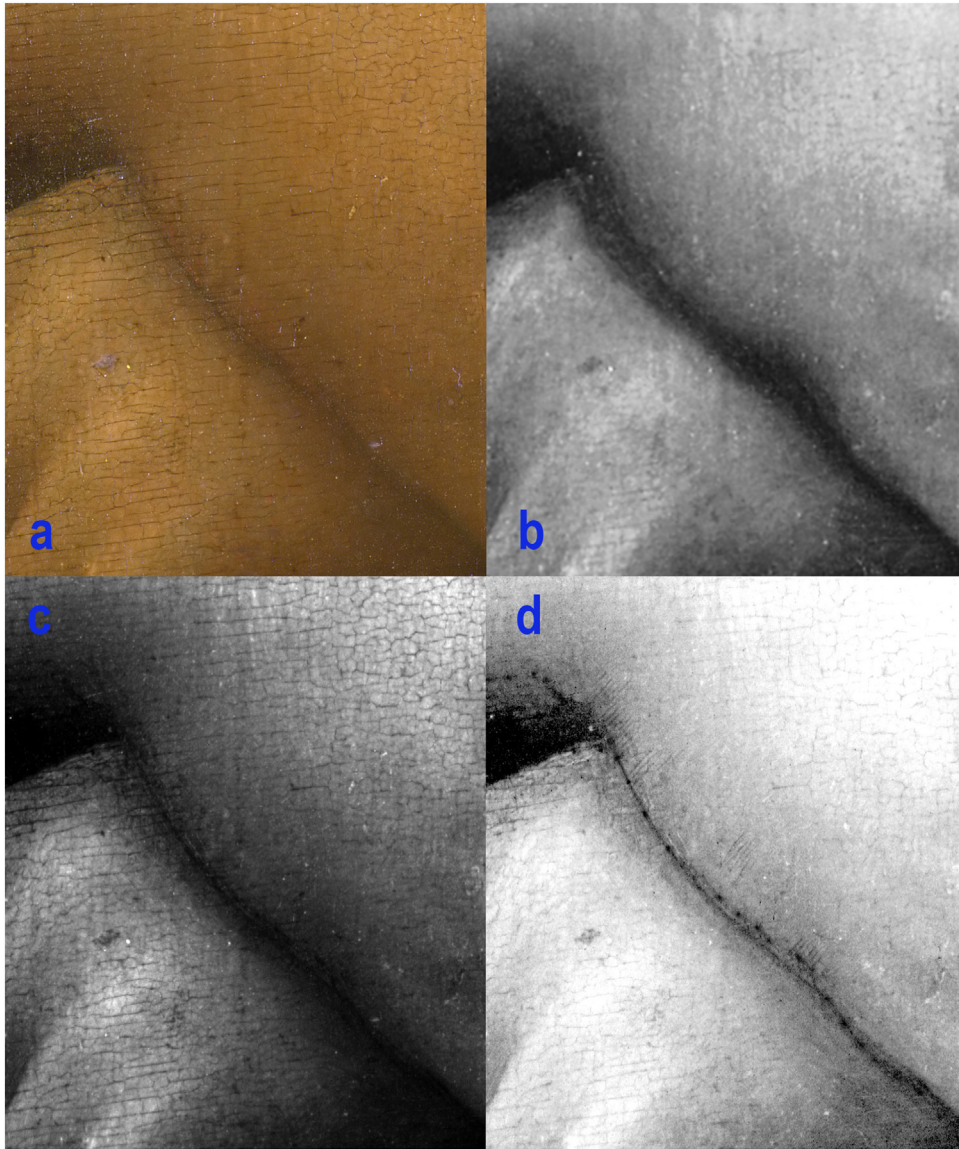


Fig. 8. Detail of *Mona Lisa*'s hands: (a) – Colour image D65 ; (b) – IR reflectography 2000 nm. © Louvre [27]; (c) – Visible reflectance R_{720} . © P.Cotte ; (d) – L.A.M. Technique. © P.Cotte.

4 IR reflectography (full portrait) made in multiple shoots with the same 16 M pixel OSIRIS camera that we used for the test board. (IR 1700 nm) [30]

Perhaps for the aforementioned reasons (see Section 4.2), these 4 methods did not allow us to see the *spolveri* present in many places (even on the enlarged one), as we uncovered with the L.A.M. technique.

The L.A.M. technique found the *spolveri* mainly in the light layers, which scatter light in the lower strata. There is more difficulty in dark areas, where the black dots are confused with their environment.

We present the discoveries made in the 3 areas in Fig. 6.

5.1. Mona Lisa's forehead

On the *Mona Lisa*'s forehead (Fig. 6 point 1), as it appears today (Fig. 7a), the edge of the veil that covers the head is represented by a simple line that regularly follows the hair limit, a few millimetres below from left to right; the enlarged Louvre's IR reflectography at 2000 nm [28] (Fig. 7b) shows us much the same image as the

NIR filter R_{900} of the multispectral camera. (Fig. 7c). No *spolvero* are visible in these images even when applying image processing to increase the contrast.

This L.A.M. image (Fig. 7d) was obtained by calculating the numerical derivative of the reflectance R_{600} , R_{640} , and R_{900} :

$$L.A.M. = \left[- \left(\frac{R_{900} - R_{600}}{2} + R_{600} \right) + pR_{640} \right] \quad (1)$$

where R_{λ} is the reflectance at wavelength λ , and p is a coefficient that increases the weight of reference reflectance R_{640} ($p = 1.064$ in the presented image).

On the L.A.M. image, we observe a *spolvero* on the forehead (drawing lines with black dots), almost at the same location, but the lines are more inclined to *Mona Lisa*'s right. This is a preparatory drawing of a face turned to the right. It outlines a different veil belonging to a previous project of Leonardo's. He draws 2 lines between which Leonardo probably designed the embroidery, as often found in contemporaneous Florentine paintings, such as the Portrait of wealthy *Maddalena Strozzi Doni* executed by Raphael in 1506. (Oil on panel 63×45 cm, Palazzo Pitti, Florence.) This finding is

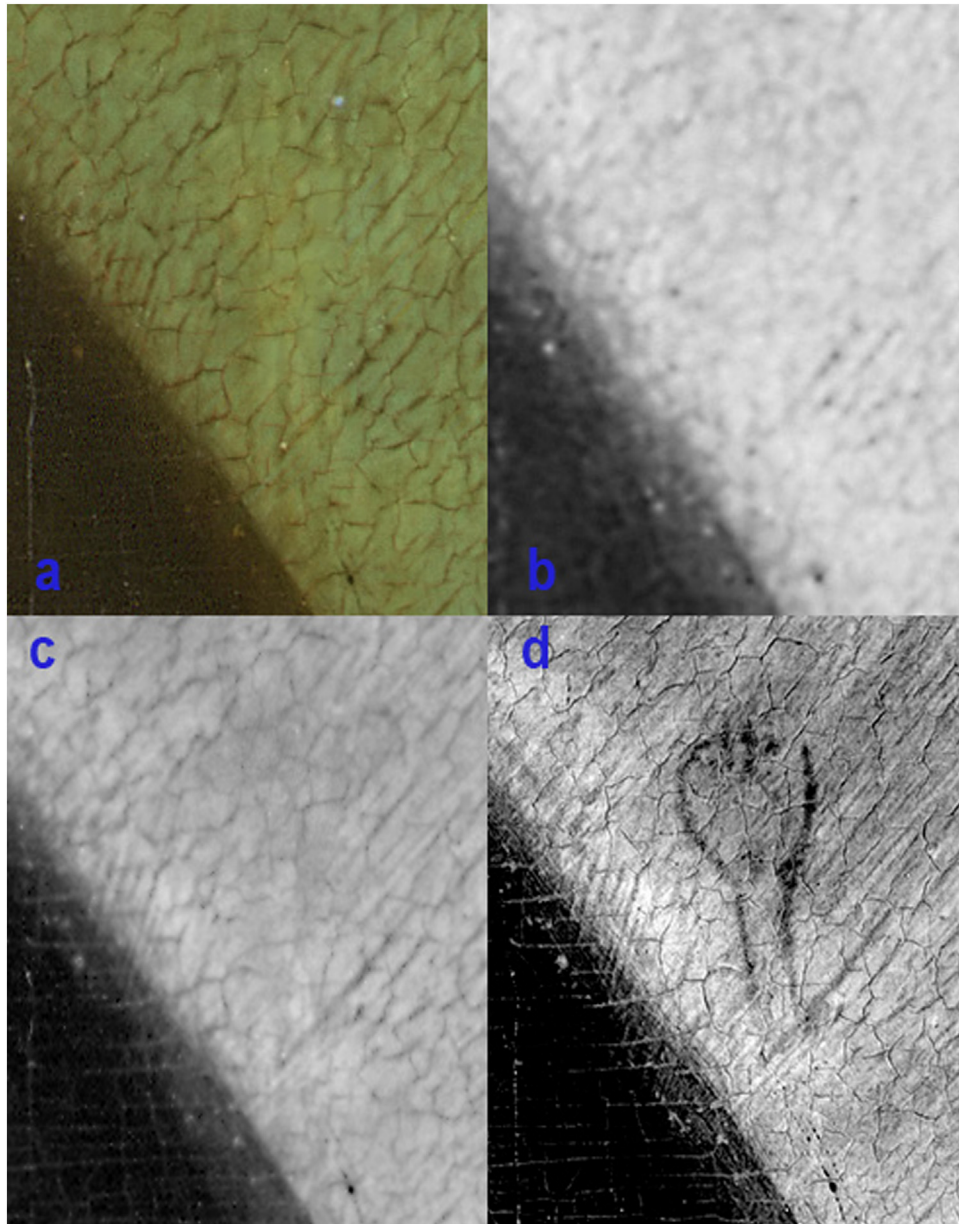


Fig. 9. Detail on *Mona Lisa's* head: (a) – Colour image D65 ; (b) – IR reflectography 2000 nm. © Louvre [28]; (c) – NIR R₈₀₀. © P.Cotte ; (d) – L.A.M. Technique. © P.Cotte.

proof that this work evolved in its composition and that Leonardo did not remain fixed on 1 version.

Notably, the L.A.M. image simultaneously shows the black dots of the transfer (highlighted in orange) and the lines drawn by the artist to connect these dots (highlighted in yellow). (Fig. 7e)

There is another horizontal line below, but it does not cover the entire width of the forehead. Some black dots appear along this line, but the contrast is too low to hypothesise that it is a *spolvero*.

5.2. *Mona Lisa's hand*

On *Mona Lisa's* hands (Fig. 6 point 2), the L.A.M. image in Fig. 8d shows a series of black dots connected by a line: This is the *spolvero* of an original preparatory drawing.

The best L.A.M. images to allow visibility of the black dots of the *spolvero* use filters only in the visible range at 720 nm and 480 nm. In this specific case, the operation is not performed directly on the reflectance but on the K_λ/S_λ ratios between the absorption K and backscattering S coefficients obtained from the reflectance

by the Kubelka-Munk function [31,32]. This operation highlights the differences in absorption and is much more sensitive than the differences in reflectance.

$$L.A.M. = \left[\left(\frac{(1 - R_{720})^2}{2R_{720}} \right) - p \left(\frac{(1 - R_{480})^2}{2R_{480}} \right) \right] \quad (2)$$

where R_λ is the reflectance at wavelength λ , and p is a coefficient to optimise the contrast ($p = 1.082$ in the presented image).

Other L.A.M. images, not presented in this article, show that the *spolvero* goes all the way around the right hand, but the contrasts of the black dots are weak and more difficult to observe.

The IR reflectography at 2000 nm (Fig. 8b), [27] does not allow us to distinguish the *spolvero*, as the visible reflectance R_{720} (Fig. 8c).

5.3. *Preparatory drawing in the sky*

A similar—but not a *spolvero*—analysis revealed this preparatory drawing (Fig. 9d) that was found in the sky to the right of *Mona Lisa's* head (Fig. 6 point 3). It is strange because it does not

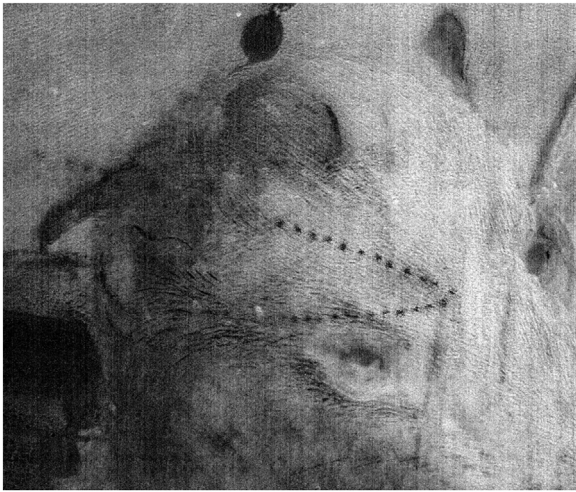


Fig. 10. *The Lady with an Ermine*, Leonardo Da Vinci. L.A.M. image. © P.Cotte The *spolvero* (line of black dots) placed behind the ermine's head draws a different project belonging to the garment. Its presence shows that perhaps the ermine was not in Leonardo da Vinci's initial project.

touch the edge of the head. It seems to belong to a previous project that Leonardo abandoned. Considering the scale of the portrait, the position near the head, the orientation, the dimensions of the object (6.5 mm × 8.2 mm), and its height of 16 mm, a possibility is that it represents a hair needle with a pearl.

For which project? For which portrait? These questions may be best answered by art historians.

This image was obtained by this calculation:

$$L.A.M. = [R_{800} - pR_{560}] \quad (3)$$

where R_{λ} is the reflectance at wavelength λ , and $p=0.852$. Stretching and equalising the histogram amplifies the dynamics of the image.

The IR reflectography [28] of Fig. 9b is a good example of the result obtained at a wavelength of 2000 nm. The IRs probably pass through the pictorial layer and the underlying drawing. The IRs, as is the NIR 800 nm (Fig. 9c), are blind to this detail in the sky.

6. Discussion and conclusion

We have demonstrated that a drawing underlying a thick layer of lead white can be highlighted by using a multispectral camera and the L.A.M. technique. IR alone is insufficient; it is necessary to combine spectral bands, especially in the visible range. The Louvre's 4 IR and NIR techniques from 800 nm to 2000 nm do not allow these drawings to be observed, probably for the reasons explained in this article. Perhaps IR cameras would have the performance required to capture them in the near future, but there would have to be improvements in SNR, spatial resolution, and spectral band.

As with IR reflectometry, a limitation of this method is when the underlying drawing is located under a very dark pictorial layer. Notably, the more absorbent (dark) the pictorial layer, the more difficult it is to detect *spolvero*. This is confirmed with the *Mona Lisa*, where the results presented correspond only to light areas containing lead white. This reason is why we assume the test board is made only with lead white. We have also detected *spolvero* in darker areas but they were less obvious. We came to the same conclusions with a test board covered with a layer of 90% lead white and mixed with 10% ultramarine blue: The L.A.M. technique remains more efficient than IR to observe the *spolvero* or the preparatory drawings. It is conceivable that multiple scans combined with HDR

software could achieve the necessary dynamics to overcome the limits of this technique.

The discovery of the *spolvero* is not surprising [10]. This method was taught in the workshop of Verrocchio, Leonardo's master, and has been highlighted in other paintings by Leonardo. We observe it in the L.A.M. image in Fig. 10 on the portrait of *The Lady with an Ermine* [2].

This discovery of the *spolvero* is important to understand how this work has evolved but also because

- 1 This is the first time that its use has been demonstrated on *The Mona Lisa*.
- 2 It places the work in a period in the history of painting during which this technique was widely used.
- 3 It proves the existence of a *cartone* (drawing on paper). A *cartone* can be copied indefinitely; perhaps other versions are made from this drawing. We are thinking of the Prado Museum's version.
- 4 It makes it possible to estimate the degrees of freedom that Leonardo allows himself during the execution of the painting.
- 5 It enriches the database with information on Leonardo's technique (e.g. measurements of hole spacing, black dots, width of the pencil line, nature of the pencil line).

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Appendices. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.culher.2020.08.004>.

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APPENDICES

Appendix A - Dynamic Range and Signal-to-Noise Ratio

Dynamic range (DR) is the ratio between the largest and the smallest values that the image can assume. It can be expressed in dB. The higher the DR, the greater the nuances and information the image offers. Signal-to-noise ratio (SNR) is a measure that compares the level of a desired signal to the level of the background noise in dB.

The multispectral camera uses a TH-7834 CCD sensor originally designed for the SPOT [15] image weather satellite and other uses. It is a 12,000 pixel linear array of a 6.5 μm square. It offers a DR of 10,000:1 [16]. Considering the manufacturer's data (Quantum Efficiency, Photo response non uniformity and Dark Signal nonuniformity) and camera operating parameters, we obtain an effective SNR of 9,230:1 or 79.3 dB. By comparison, a camera with a CMOS sensor typically has an effective SNR of approximately 446:1 or 53 dB.

The visible or invisible information the image can only be extracted by algorithms under the condition that it is not drowned out by the electronic noise of the image. To amplify weak signals, it is therefore important to have a source of information with the highest possible DR and SNR. For example, a weak signal when digitised with a usual CMOS sensor would only contain 2 bits (4 grey levels)—almost unusable for paint analysis—but with the multispectral camera's CCD, the same signal would have 5.7 bits (52 grey levels) and would thus become relevant information.

The camera digitises each filter individually, and this allows optimisation of the exposure time of the pixels to light to reduce the amplification gain and thus obtain a maximum SNR for each filter. This is a considerable technical advantage compared with hyperspectral cameras, which have an SNR optimised for a wavelength but are often much worse at the ends of the spectral domain.

Appendix B - Spatial resolution - Contrast Transfer Function

The camera uses a 210 mm focal length optic and a symmetrical lens formula. Geometric distortion is low and not measurable. The CTF of a camera is the measure of its ability to reproduce spatial frequencies (details of an image). The measurements were made on the ISO 16097-1 test pattern [17], which includes pairs of black and white lines at different frequencies. The setting of the camera is 1200 dpi, 1 CCD pixel of 6.5 μm sees 21 μm on the test pattern. In practice, the CTF is calculated by using the line pattern contrast determined at the different spatial frequencies of the target. The minimum spatial frequency f_0 is obtained over large bright areas in the edges of the target.

One of the main optical characteristics of this camera is its ability to memorise a specific focus for each filter with 2 advantages: to always have a maximum CTF (Table A1) for each wavelength and to cancel sagittal and longitudinal chromatic aberration, and defects are inevitable otherwise. This is a second considerable technical advantage compared with hyperspectral cameras because the focus and therefore the resolution are optimised for 1 wavelength and are significantly worse at the edge of the spectrum. For comparison purposes, measurements made for the 400, 760, and 1000 nm filters while maintaining focus on the central band at 560 nm show poor CTFs.

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C(f) on raw files		Variable focus for 13 Filters from 400 nm to 1000 nm and Panchro without filter														Fixed Focus 560 nm		
Cycles/mm	size	400	440	480	520	560	600	640	680	720	760	800	900	1000	Panchro	400	760	1000
f_0		77%	83%	84%	83%	79%	83%	83%	80%	81%	81%	84%	72%	53%	92%	43%	67%	24%
6 c/mm	83 μ m	61%	65%	64%	61%	65%	64%	66%	62%	59%	59%	58%	43%	42%	54%	6%	13%	3%
8 c/mm	63 μ m	52%	60%	52%	50%	52%	53%	54%	51%	48%	49%	47%	35%	30%	39%	6%	11%	2%
12 c/mm	42 μ m	31%	35%	35%	28%	32%	37%	37%	37%	29%	32%	29%	22%	17%	23%	5%	2%	2%
24 c/mm	21 μ m	8%	10%	12%	6%	5%	11%	10%	13%	10%	10%	8%	5%	10%	8%	2%	2%	2%
Focus adjust. (210 mm ∞)		278.60	278.20	278.00	278.00	277.90	278.20	278.30	278.50	278.70	278.90	279.20	279.80	280.30	275.80	277.90	277.90	277.90

Table A1: CTF values for all filters of the Lumiere Technology multispectral camera with a specific focus for each filter individually. The CTFs of the 400, 760, and 1000 nm filters are also given with a focus identical to the 560 nm filter at 277.90 mm.

It is possible to slightly improve the CTF by software processing algorithms such as deconvolution matrices. However, this improvement is at the cost of a significant decrease in image dynamics (DR and SNR) and is not used for L.A.M. analysis of multispectral imaging.

Appendix C - Binning to increase the DR and SNR

One advantage of having a hyper high-resolution image of 240,000,000 pixels with the multispectral camera is that it allows us to increase the dynamic range of the image by using the binning method [19]. Binning is usually performed on the sensor by combining the outputs of neighbouring photosites, or by mathematical algorithms. It reduces the resolution but increases the DR and the SNR by lowering the background noise.

However, the excessive reduction of the resolution with binning is also a loss of information; there is therefore a compromise between a gain in dynamics and loss of spatial resolution.

We use a binning of max 4x4 pixels and therefore have a gain in SNR of 10 dB.